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Seismogenic structure of the 2016 Ms6.4 Menyuan earthquake and its effect on the Tianzhu seismic gap

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ABSTRACT

On January 21, 2016, a strong earthquake with a magnitude of Ms6.4 occurred at Menyuan, Qinghai Province of China. In almost the same region, there was another strong earthquake happened in 1986, with similar magnitude and focal mechanism. Based on comprehensive analysis of regional active faults, focal mechanism solutions, precise locations of aftershocks, as well as GPS crustal deformation, we inferred that the Lenglongling active fault dips NE rather than SW as suggested by previous studies. Considering the facts that the 2016 and 1986 Ms6.4 Menyuan earthquakes are closely located with similar focal mechanisms, both of the quakes are on the north side of the Lenglongling Fault and adjacent to the fault, and the fault is dipping NE direction, we suggest that the fault should be the seismogenic structure of the two events. The Lenglongling Fault, as the western segment of the well-known Tianzhu seismic gap in the Qilian-Haiyuan active fault system, is in a relatively active state with frequent earthquakes in recent years, implying a high level of strain accumulation and a high potential of major event. It is also possible that the Lenglongling Fault and its adjacent fault, the Jinqianghe Fault in the Tianzhu seismic gap, are rupturing simultaneously in the future.

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1. Introduction

On 21 January 2016, an earthquake with the magnitude of Ms6.4 occurred in Menyuan County, Qinghai Province of China. According to China Seismic Network Center (CENC), the epicenter of the earthquake is at 37.68°N, 101.62E° (Fig. 1b), with a focal depth of about 10 km. Field investigations revealed that the intensity of the meizoseismal area is VIII degree. The whole Qinghai Province, as well as some places in Gansu Province, such as Lanzhou, Wuwei, Zhangye, and Jinchang have been shaken by the quake to varied degrees. The long-axis of the isoseismal lines is NWW (http://news.ceic.ac.cn/CC20160121011313.html), in agreement with the strikes of a series of sub-parallel faults such as the Lenglongling, Menyuan, Minle-Damaying, and Huangcheng-Shuangta faults [1]. As the event took place in a sparsely populated area, no serious casualties and property loss were reported. However, it caught the attention of the seismological society because there was another Ms6.4 earthquake happened in 1986 at almost the same place with similar focal mechanism. Besides, there were many middle-sized events, such as 1991 Ms5.1 and 2013 Ms5.3 earthquakes, occurred around the same area. Considering that all these events are close to the Lenglongling active fault, which is part of the well-known Tianzhu seismic gap [2,3], people are increasing their concerns about the potential great earthquakes in the gap. To clarify the relationship between the 2016 Ms6.4 Menyuan earthquake and the Lenglongling Fault is of great significance for understanding the mechanism of recurrence of the earthquakes and assessing the seismic risk of this region. In this work, we based on the data of regional active faults, focal mechanism solutions, precise locations of aftershocks, as well as GPS crustal deformation to explore the seismogenic structure of the 2016 Ms6.4 Menyuan earthquake, and further discuss the future tendency of strong earthquakes in the Tianzhu seismic gap.

2. Tectonic setting

The 2016 Ms6.4 Menyuan earthquake took place in the North Qilian fold zone of the northeastern margin of the Tibetan Plateau. Its north side of the seismogenic region is the Hexi corridor transition belt, and the south side is the Middle Qilian uplift zone. In a range of 50 km surrounding the epicenter, there are series of NW-NWW trending active faults (Figs. 1b and 2), which are Minle-Damaying, Huangcheng-Shuangta, Lenglongling and Menyuan faults from north to south. Of them, the Minle-Damaying Fault is a thrust fault and used to be active in Late Pleistocene, dipping SW linking the west end of the Huangcheng-Shuangta Fault in a left-stepping manner. No historical earthquakes were documented in relation with this fault. The Huangcheng-Shuangta Fault, with a length of about 120 km, dips SW, dominated by thrust with a sinistral-slip component [1], which is considered to be responsible for the 1927 Gulang M8.0 earthquake [4–6]. The

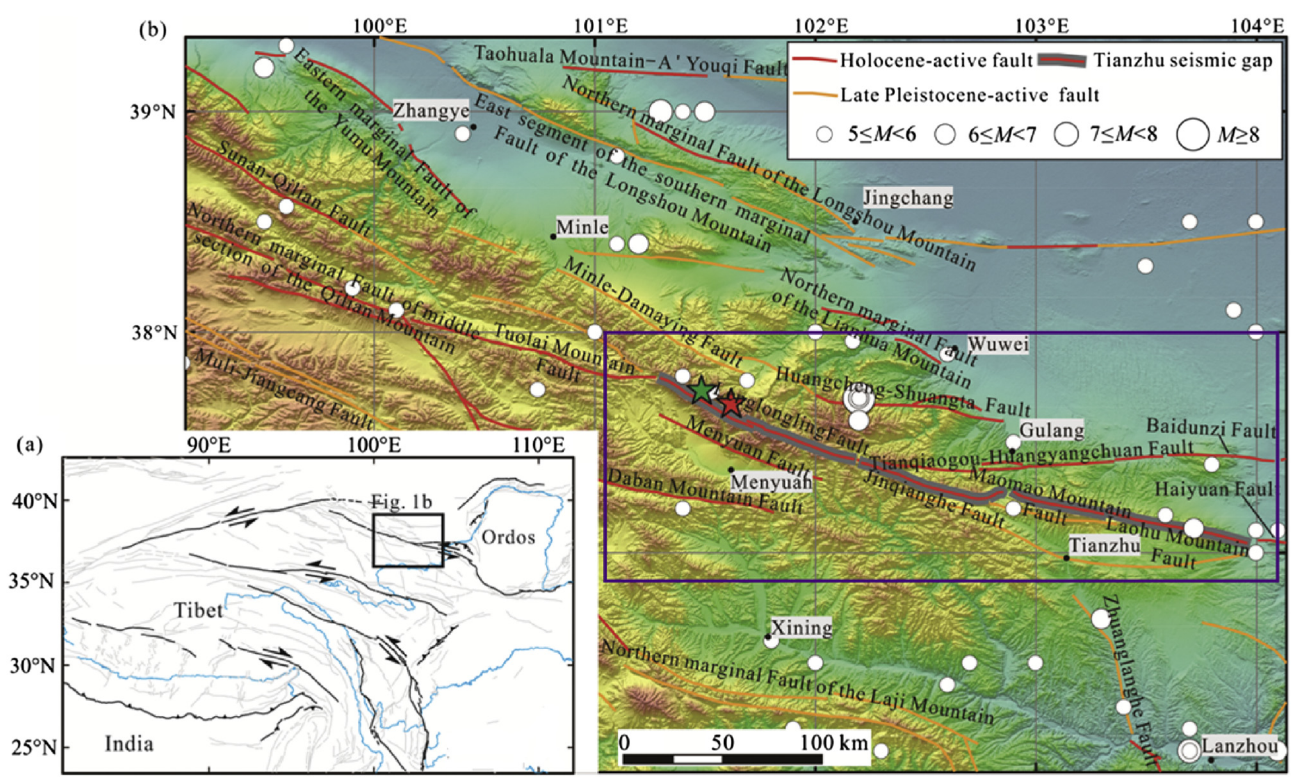

Fig. 1 – Maps (a,b) showing the seismotectonics around the epicenter of the 2016 Ms6.4 Menyuan earthquake. The red star indicates the epicenter of the 2016 Menyuan Ms6.4 earthquake, and the green star, the 1986 Ms6.4 Menyuan earthquake (from USGS); the purple rectangle, the study area of Fig. 2a.

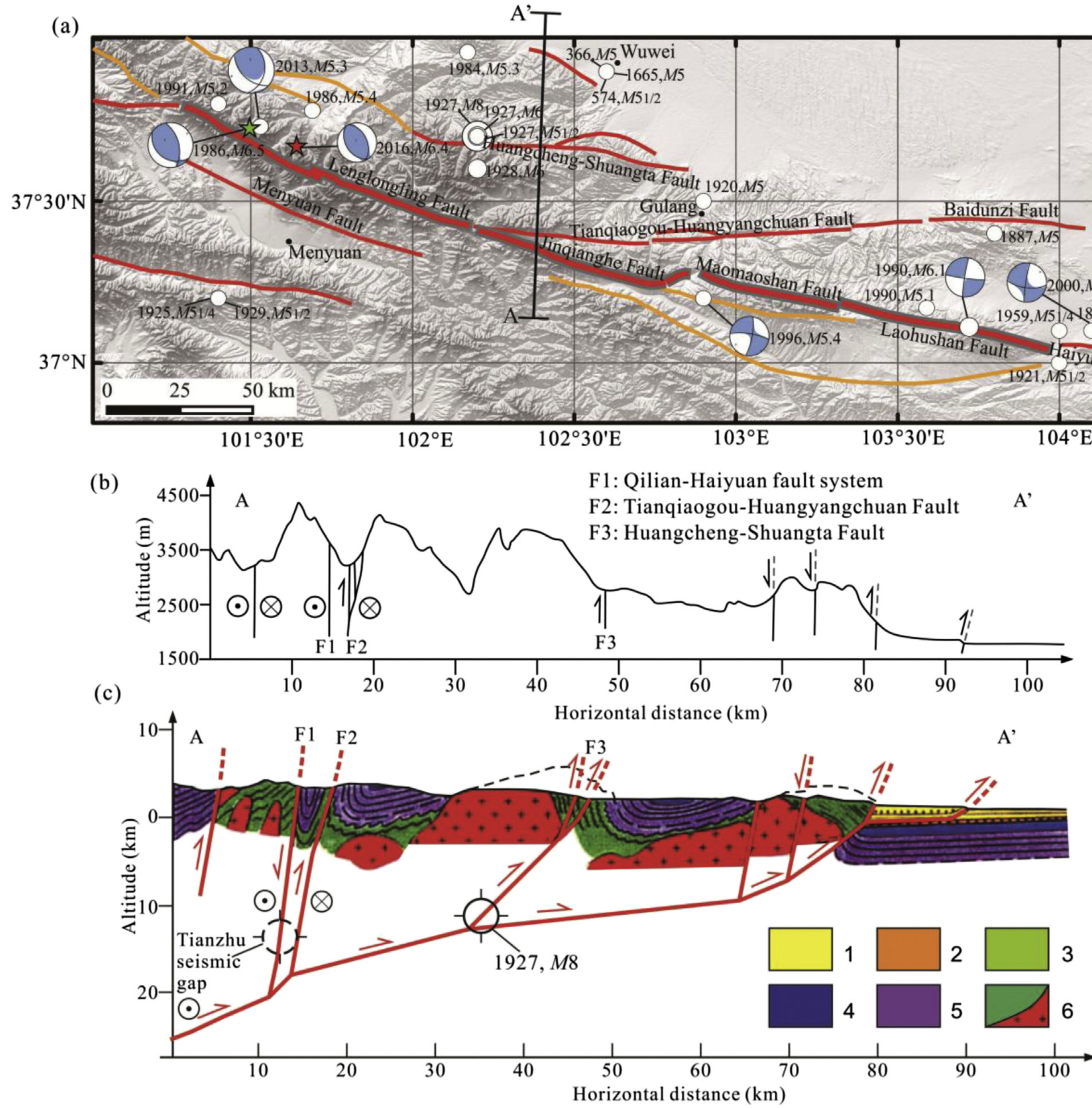

Fig. 2 – Sketch of shallow and deep structures of the Tianzhu seismic gap. (a)The active faults in the Tianzhu seismic gap, and the seismic mechanisms of some historic earthquakes around (From USGS). (b)The profile A–A′ in Fig. 2a showing topography and distribution of active faults [2,9]. (c)The profile A–A′ in Fig. 2a showing the tectonic style in deep, in which,1 stands for upper Pleistocene-Holocene; 2, Neogene; 3, Cretaceous; 4, Jurassic; 5, Carboniferous-Triassic; 6, Pre-Devonian metamorphic and igneous basement [2,9].

Lenglongling Fault is part of the Qilian-Haiyuan active fault system, dominated by sinistral-slip with a considerable thrust component. The Menyuan Fault lies on the north edge of the Mengyuan Basin with a controlling role on the development of the basin. Since Late Pleistocene, the activity of this fault has been weakened gradually [7].

Among the sub-parallel faults aforementioned, the Lenglongling Fault is most active since Late Quaternary time, with average horizontal slip rate of 4.5–10 mm/yr or greater [2,8]. As shown in geologic cross sections [2,9] (Fig. 2b and c), the several sub-parallel NW-NWW trending faults in the Menyuan seismogenic area probably belong to the same thrust faults system with sinistral-slip at depth. Within this fault system, the Haiyuan and Huangcheng-Shuangta faults are the causative faults of the 1920 Hauyian *M*8.5 and 1927 Gulang *M*8.0 large earthquakes, respectively. Previous research shown that the Tianqiaogou-Huangyangchuan fault (also called Gulang fault) probably also ruptured during the 1927 Gulang event [10]. Thus the fault section Lenglongling-Jinqiang River–Maomao Mountain–Laohu Mountain not involved in the two great earthquakes is a seismic gap named the “Tianzhu seismic gap”, which has long been highly concerned by researchers of China and abroad to have a potential of a *M*8 earthquake in the future

[2,3]. The 2016 Ms6.4 Menyuan earthquake occurred just at the west end of this gap, and also several strong earthquakes were recorded nearby since 1986. So the issue on the causative fault of the 2016 Ms6.4 Menyuan earthquake directly links to the seismic risk assessment of the Tianzhu seismic gap.

3. Inference of seismogenic structure for 2016 Ms6.4 Menyuan earthquake

As the 1986 and 2016 Ms6.4 Menyuan earthquake did not produce visible rupture on the ground, it makes their causative faults unclear. The focal mechanism solutions from USGS and CENC suggest that the seismogenic fault of the 2016 event is a thrust trending NW, dipping NE with an inclination of more than 55° (Fig. 2a), and the focal depth is about 10 km. The precise locations of aftershocks (Fig. 3c) show that the rupture plane of this fault is very steep or nearly vertical. The data from USGS also indicate that the focal mechanism solutions of the 2016 Menyuan earthquake are very similar to those of the 1986 Ms6.4 event and the 2013 Ms5.3 event (Fig. 2a). These clues allow us to choose some NE trending steeply dipping faults with obvious thrust property among the major active faults around the epicenter of the 2016 Ms6.4 Menyuan earthquake as the possible causative structures.

As mentioned previously, there are several NW-NWW active faults around the epicenter, such as the Minle-Damaying, Huangcheng-Shuangta, and Lenglongling faults. The strikes of all these faults are consistent with the focal mechanism solutions of the 2016 Ms6.4 Menyuan earthquake. Considering the constrains that the causative fault should dip NE at an angle greater than 55°, in combination with the focal depth of about 10 km, the most qualified causative faults should be located south of the epicenter within a distant of about 5 km or closer. Thus the Minle-Damaying and Huangcheng-Shuangta faults, which lie north of the epicenter over 15 km apart, are excluded from the causative faults for the 2016 Menyuan earthquake, and the remained Lenglongling fault seems the only candidate. However, whether this fault dips NE or SW is a controversial issue in previous studies: Geological sections in the regional geological map inferred that the Qilian-Haiyuan fault system, which includes the Lenglongling fault, dips SW at a big angle at depth [2,9]. While recent field investigations on the surface found some evidences that this fault dips NE at an angle over 60° [3,11,12] (Fig. 4). Here we try to use GPS crustal deformation data, from the perspective of geodesy, to judge the dipping direction of Lenglongling Fault:

In the northeastern margin of the Tibetan plateau, two national scientific infrastructure projects named "Crustal Movement Observation Network of China" and "Tectonic and Environmental Observation Network of Mainland China" have deployed dense GPS stations, and accumulated high-quality GPS observation data since 1999 [14,15]. Here we chose the data from 10 continuous GPS stations and 74 campaign-mode GPS stations within 200 km of the seismogenic region. By rigorous data processing, we obtained GPS velocities of these stations in a Eurasia-fixed reference frame (Fig. 5). It is clearly shown that the velocities on the south side of the Qilian-Haiyuan fault system are generally larger than those on the north side. The

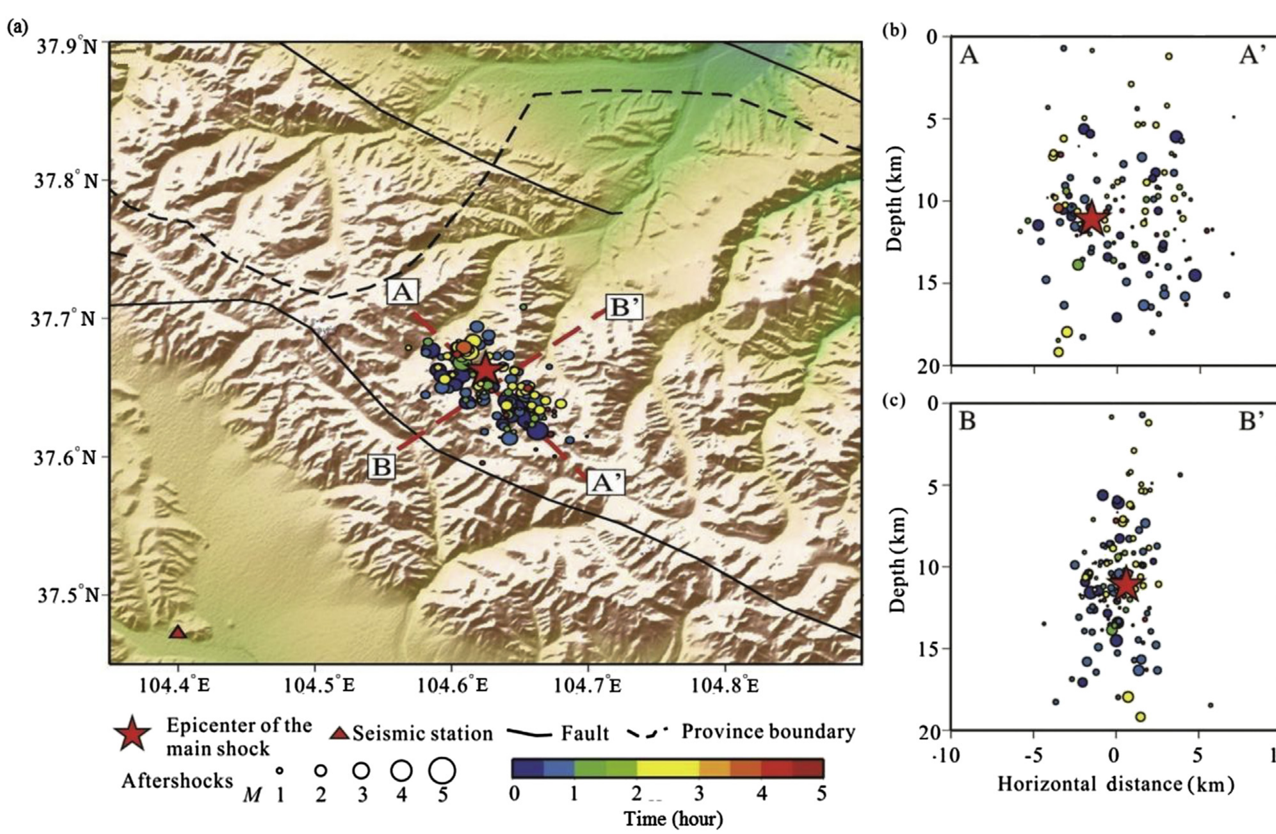

Fig. 3 – Results of precise relocation of aftershocks associated with the 2016 Ms6.4 Menyuan earthquake [13].

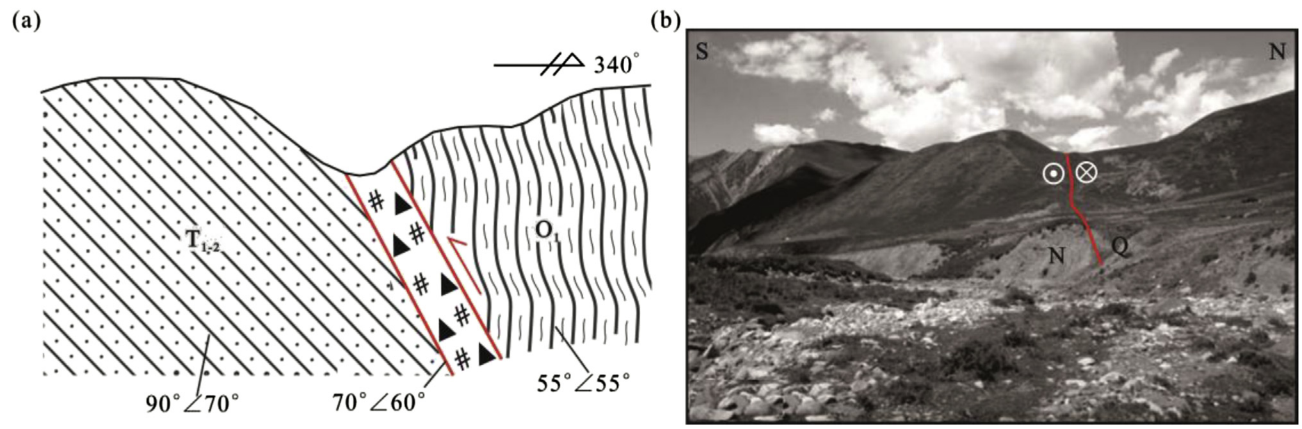

Fig. 4 – Two typical fault profiles cross the Lenglongling Fault. (a) Profile modified after the data [11]. The footwall of the fault is consists of Triassic sandstone, and the hanging-wall is Ordovician metamorphic rocks. (b) Profile modified after the data [3]. The footwall of the fault is consists of Neogene, and the hanging-wall is Quaternary. Both of the profiles reveal that the Lenglongling fault dips NE.

average crustal motion rate is 9.5 mm/yr for the 29 stations in the south and 4.0 mm/yr for the 26 stations in the north, which indicates a difference of 5.5 mm/yr.

In theory, the motion manners (i.e. strike-slip and dip-slip) and rates of active faults in a region determine the features of the GPS velocity field. If the geometric parameters (i.e. spatial distributions, dip directions, dip angles, and locking depths) and motion parameters (rates of strike-slip and dip-slip) of all active faults in a region are known, it is possible to calculate a definite GPS velocity field by using the elastic half-space dislocation model [4]. Conversely, with the constrains of a dense enough GPS velocity field, we could inverse or infer some geometric and motion parameters, such as slip rates,

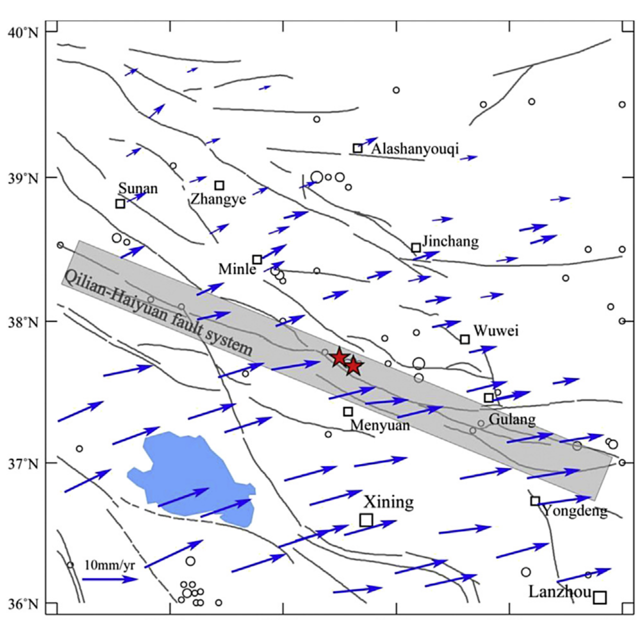

Fig. 5 – Horizontal GPS velocities around the epicenter of the 2016 *Ms*6.4 earthquake (relative to stable Eurasia). It can be seen that the GPS velocities are obviously different between the two sides of the Qilian-Haiyuan fault system.

locking depths, dipping directions and dipping angles of the regional active faults. Based on this understanding, we establish the geometric models for the major faults in the study area (Fig. 5, Table 1), including segmentations and the geometric parameters aforementioned. Notice that because the dipping direction of the Tuolai Mountain–Lenglongling-Jinqiang River fault section is not certain to be SW or NE, we temporally assume it is almost vertical.

Based on the simple geometric models of the faults above (Table 1), and with the constraints from GPS velocities, we use the elastic half-space dislocation mode [16] to invert slip rates of all the major faults. The software and method used can be found in the paper of Gan et al. [17]. The results show that the slip rates and senses of the faults from inversion are roughly in accordance with those from geologic observations. It means that if these faults are assigned reasonable senses and rates of motion, the modeling results can well fit the observed GPS velocity field (Fig. 5). On the basis of this preliminary inversion, we trially assume that the Tuolai Mountain–Lenglongling-Jinqiang River fault dips SW and NE, respectively, with dip angles of 65°. Then we compare the fitting degrees of the models to the observed GPS velocities under these two different assumptions. The result shows that in the case of dipping NE, the sum of weighted least squares residuals of the GPS velocities decreases by 41% comparing with the preliminary model, while in the case of dipping SW, it decreases by 30%. Thus, we infer that the Lenglongling Fault should be a dip-slip structure, dipping NE, which is consistent with geological observations (Fig. 6).

In summary, based on the direct evidences from geological field surveys and the indirect evidence from the inversion of GPS crustal deformation model, we suggest that the Lenglongling fault is a thrust with sinistral-slip, dipping NE. Considering the facts that the 2016 and 1986 Ms6.4 Menyuan earthquakes are closely located each other with similar focal mechanisms, both of the quakes are on the north side of the Lenglongling Fault and adjacent to the fault, and the fault is dipping NE direction, we suggest that the Lenglongling Fault should be the seismogenic structure of the two events.

Table 1 – Model parameters and inverted motion rates of the major active faults around 2016 Ms6.4 Menyuan earthquake.

Fault name		Locking depth (km)	Dipping direction	Dipping angle (°)	Inverted rate	
					Strike-slip mm/a	Dip-slip mm/a
Qilian-Haiyuan fault system	Jinqianghe-Maomao Mountain segment	15	NE?/SW?	65	−8.2 ± 1.4	4.0 ± 0.8
	Lenglongling segment	15	NE?/SW?	65	−4.6 ± 0.8	5.9 ± 0.8
	Tuolai Mountain segment	15	NE?/SW?	65	−5.3 ± 0.6	6.7 ± 0.7
Xunhua-Nan Mountain fault system		15	N	70	−0.1 ± 0.2	2.4 ± 0.2
Riyue Mountain fault system		15	SW	70	2.6 ± 0.1	−1.5 ± 0.2
Huangcheng-Shuangta fault		15	S	70	−1.0 ± 0.5	1.8 ± 0.2
Tianqiaogou-Huangyangchuan fault		15	N	70	−2.0 ± 0.1	2.0 ± 0.2
Qilian Mountain north edge fault system		15	S	70	−0.5 ± 0.2	3.0 ± 0.8
Longshou Mountain fault system		15	S	70	0.1 ± 0.1	2.6 ± 0.8

Notes: Strike-slip rates: positive for dextral. Dip-slip rates: positive for thrust.

4. Discussion on seismic risk of the Tianzhu seismic gap

Geologic data and focal mechanism solutions of several historical earthquakes (Fig. 2a) show that the Lenglongling Fault is dominated by thrust, the Jinqiang River Fault has both sinistral-slip and thrust, and the Laohu Mountain and Maomao Mountain faults are of dominant strike-slip [18]. It means that every fault or fault segment in the Tianzhu seismic gap has its obviously distinct features of motion. From spatial distributions of historical earthquakes, we notice that except the Jinqiang River Fault, the other three faults have generated *M*5 or greater earthquakes, of which the Lenglongling has the most frequent earthquakes. From the fault distribution map, it can be seen that there is a "remarkable" left-stepping area exceeding 7 km between the Jinqiang River fault and Maomao Mountain fault, i.e. the Tianzhu basin. While there are no considerable step areas between the Lenglongling and Jinqiang River faults and between Maomao Mountain and Laohu Mountain faults. Lettis et al. [19], based on the statistics of seismic cases, concluded that a cascade seismic rupture is usually hard to breakthrough a step area of a fault when its width exceeds 5 km, while such rupture is easy to breakthrough a step area with a width less than 2 km. Thus, for the Tianzhu seismic gap, each of the four fault segments (Lenglongling, Jinqiang River, Maomao Mountain and Laohu Mountain faults) could be a secondary gap to break independently to produce earthquakes with the magnitude of *M*7-7.5 in the future, estimated by the empirical formulas based on the fault length [20–22]. It is not like that all its four fault segments break simultaneously in one earthquake. But it is possible that the Lenglongling and Jinqiang River faults constitute a secondary gap to break simultaneously to produce a large earthquake with $M \approx 8$. So do the Maomao Mountain and Laohu Mountain faults. For the Lenglongling-Jinqiang River segment, relatively frequent strong earthquakes on the adjacent Lenglongling fault indicates a high level of strain accumulation, implying a relatively emergent risk of major seismic events in the future.

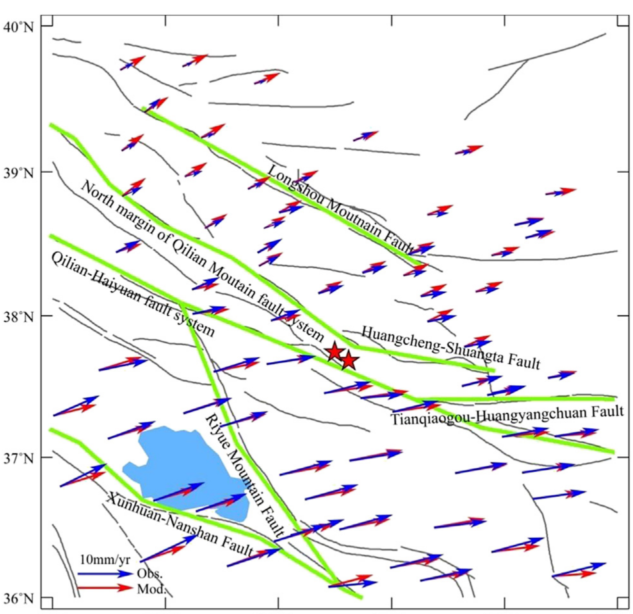

Fig. 6 – Geometric model of the major active faults and the GPS velocities around the seismogenic area of the 2016 and 1986 Ms6.4 earthquakes. The grey thin lines indicate active faults, and the green thick lines, the modeled major active faults. The blue vectors indicate observed GPS velocities, and the red vectors arrows, calculated velocities using the elastic half-space dislocation mode.

5. Conclusions

Based on comprehensive analysis of regional active faults, focal mechanism solutions, precise locations of aftershocks, as well as GPS crustal deformation, we inferred that the Lenglongling active fault dips NE rather than SW as suggested by previous studies. Considering the facts that the 2016 and 1986 Menyuan *Ms*6.4 earthquakes are closely located each other with similar focal mechanisms, both of the quakes are on the north side of the Lenglongling Fault and adjacent to the fault, and the fault is dipping NE direction, we suggest that the fault should be the seismogenic structure of the two events. The Lenglongling fault, together with Jinqiang River, Maomao Mountain and Laohu Mountain faults, formed the Tianzhu seismic gap in the Qilian-Haiyuan active fault system. Each of the four faults of the Tianzhu seismic gap has its evidently distinct features of activity. Each of the four sub-gaps has the potential of about *M*7-7.5 earthquakes in the future. The frequent earthquakes along the Lenglongling Fault in recent years imply a high level of strain accumulation, and thus a relatively emergent risk of major seismic events in the future. It is also possible that the Lenglongling and Jinqiang River faults are rupturing together to produce a large earthquake with $M \approx 8$.

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